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The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook

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A B S T R A C T

Plug-in hybrid electric vehicles (PHEVs) are the next big thing in the electric transportation market. While much work has been done to detail what economic costs and benefits PHEVs will have on consumers and producers alike, it seems that it is also important to understand what impact PHEVs will have on distribution networks nationwide. This paper finds that the impact of PHEVs on the distribution network can be determined using the following aspects of PHEVs: driving patterns, charging characteristics, charge timing, and vehicle penetration. The impacts that these aspects of PHEVs will have on distribution networks have been measured and calculated by multiple authors in different locations using many different tools that range from analytical techniques to simulations and beyond. While much work has already been completed in this area, there is still much to do. Areas left for improvement and future work will include adding more stochasticity into models as well as computing and analyzing reliability indices with respect to distribution networks.

Contents

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are a new and upcoming technology in the transportation and power sector. As they are defined by the IEEE, these vehicles have a battery storage system of 4 kWh or more, a means of recharging the battery from an external source, and the ability to drive at least 10 miles in all electric mode [1]. These vehicles are able to run on fossil fuels, electricity, or a combination of both leading to a wide variety of advantages including reduced dependence on foreign oil, increased fuel economy, increased power efficiency, lowered greenhouse gas (GHG) emissions and vehicle-to-grid (V2G) technology [2–4]. These claims are backed by data suggesting that fueling a PHEV would cost the equivalent of 70 cents per gallon of gasoline when electricity costs 10 cents per kWh [4] and that an all electric driving range of 40 miles could lower oil consumption by two-thirds [4].

The most current example of a PHEV is the Toyota Prius. This vehicle could originally be converted from a HEV into a PHEV using

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an aftermarket kit and is now being manufactured as a both a hybrid electric vehicle (HEV) and PHEV. Other vehicles that are either electric vehicles (EV), hybrid electric vehicles (HEV), or PHEVs and are currently available or will soon appear on the market include the Chevy Volt (2010), Cooper Mini E (current), Fisker Karma (2010), Nissan LEAF (2010), and the Tesla Roadster (current) [4]. With these advantages in mind, an estimate has been made that there will be a market penetration of roughly 1.5 million PHEVs in 2016 increasing to over 50 million in 2030 with roughly 25% of all newly purchased vehicles being PHEVs [5]. The US government has also put their full faith and credit behind PHEV initiatives by setting a goal of 1 million PHEVs on the road by 2015 and by developing a set of incentives that allow PHEVs to repay its full value to its owners within the first 25% of its life span [4]. These incentives were put in place as part of the American Recovery and Reinvestment Act of 2009 and allow for credits between $2500 and $7500 for newly purchased, four or more wheeled PHEVs that weigh no more than 14,000 pounds. Vehicle conversion is granted a 10% reimbursement to a maximum of $4000.

Many works have focused on economic models, economic incentives, loading profiles, and charging profiles for these new vehicles, but very few works have been interested in the impact of PHEVs on the distribution grid. As these new vehicles will be a significant new load on the power grid while also requiring some infrastructure changes, it is proper to study their effect on distribution as well as their effect on generation. This paper will survey all current studies on the effects of PHEVs on the distribution grid, compare and contrast those same studies, and suggest potential future work.

2. Literature review

The basic effects that PHEVs will have upon the grid based upon their characteristics are covered by Hadley [6]. PHEV characteristics are broken down into vehicle characteristics, charging characteristics, and when PHEVs are plugged in [7]. The impacts of PHEVs are determined through regional grid analysis based upon the number of vehicles, vehicle demand profile, and the effect that demand has on supply and demand. The paper does not come to any specific conclusions about optimal charging patterns or grid reliability, but it does suggest that work must be done to further investigate how PHEVs will impact the grid.

Perhaps the most important point that this article makes with regards to PHEVs and the distribution grid is that for quite some time any analysis of the distribution grid has been ignored because it has been assumed that either enough capacity exists or that PHEV adoption will occur slowly enough that utilities will have more than enough time to adjust and reinforce the current networks. This may or may not be the case as governments begin putting regulations in place to curb the effects of global warming and greenhouse gases.

The impact of charging PHEVs on a typical distribution feeder in Blacksburg, VA is examined in Shao et al. [8]. The network consists of five homes and two PHEVs, each of which is a Chevy Volt. Two charging strategies are considered: All PHEVs charging at 6 p.m. and all PHEVs charging at off-peak hours. The first case represents the worst case and results in a transformer load increase to 68/52% in winter/summer. The latter case results in a transformer load increase to 58/52% in winter/summer.

As neither of these scenarios results in transformer overloading, the cases are reconsidered using quick charging—the ability of the consumer to use a higher voltage outlet in order to charge their PHEV in less time. This results in a transformer overload only when quick charging starts at 6 p.m. No other scenarios create an overload, though they do push the transformers to roughly 98% of their limits.

The final scenario investigated involves five PHEVs per distribution transformer. As this will obviously overload the transformer, two new methodologies for charging are suggested: PHEV stagger charge and household load control. Stagger charge staggers the charging time of PHEVs while household load control allows consumers the choice to shed some non-essential loads in order to recharge their PHEV more quickly. Neither of these scenarios creates an overload, but they do become economically unwise suggesting that consumers should attempt to avoid these situations.

The conclusion of this paper is that the addition of PHEVs creates a new load for the distribution grid, but that this load should be manageable through advanced and smart techniques such as the advanced metering infrastructure (AMI). Despite this conclusion, the authors suggest further research into large fleets and their effect on the distribution grid. The strength of this paper is fourfold: it uses a very simple system for its analysis—five homes, two PHEVs, and one 25 kVA feeder, it builds PHEV load curves based upon battery charge and discharge characteristics, it proposes and tests multiple charging scenarios, and it incorporates smart charging techniques. These are all important traits that any PHEV study should include. As such, this paper lays a strong base for future studies of PHEVs on the distribution grid. Future work based on this paper will surely include the analysis of larger penetrations of PHEVs on a wider distribution network.

The New York ISO Report [5] shows that the EPRI/NRDC expects a PHEV electric load increase of 8000 GWHs/year in New York while the ORNL study shows an increase of 7000 GWH/year, roughly a 2% increase in expected growth of electric load. Basically, the increase due to PHEV usage is expected to be relatively small. This paper also shows that with charging demands for PHEVs between 1 and 6 kWh, the load increase is roughly equivalent to doubling the current air conditioning load. It is also noted that while the distribution system has not yet been examined in detail, studies have begun through Consolidated Edison Company to ensure that the distribution grid is capable of handling PHEVs charging between 1 and 6 kWh.

Again, this study is a good starting point for the analysis of the distribution grid in New York. Though, while the increased load in the coming years is predicted to be relatively small, the true danger lies in how this load will impact the distribution grid. Distribution grids are not typically built to handle a large amount of increased loads. As this paper suggests, further work must be done to analyze what impact the addition of PHEVs to the electrical grid in New York will have on the distribution system.

The impact on the Belgium distribution grid through the analysis of current Belgium traffic and driving patterns is discussed in Clement et al. [9]. The important section of this paper examines the load flow analysis when PHEVs are added into the distribution grid. Three different cases of uncontrolled charging are examined: charging starts between midnight and 2 a.m., charging starts between 6 and 8 p.m., and charging during the day. These charging profiles are examined on a 34 node IEEE test feeder across low and high load scenarios in both summer and winter with four different penetration levels of PHEVs: 0%, 10%, 50%, and 100%.

The paper concludes that the integration of PHEVs deeply affects the power losses and voltage deviations in the distribution grid and that these changes are far too essential to ignore. This is a very important statement that must not be discarded, especially in a small country like Belgium. The impacts of PHEVs on the distribution grid must be measured and quantified in order to preserve the reliability of the electric grid.

A quadratic and dynamic programming model for assessing the impacts of PHEVs on the distribution grid of Belgium when PHEVs are charged at home is developed in Clement et al. [10]. Both the quadratic and dynamic programming techniques are applied using both deterministic and stochastic methods. The input variables in

both cases are the daily/hourly load profiles. In the deterministic case the load profiles are static. In the stochastic case the load profiles are transformed into probability density functions and are used to generate 2000 different loading scenarios that are optimized and compared. Both give similar results with the quadratic programming being more accurate as it works over a continuous solution space while the dynamic programming method works over a discrete solution space.

In order to determine impacts on the distribution grid the simulation is run for two different scenarios: uncoordinated charging and coordinated "smart" charging. The losses for the distribution grid during uncoordinated charging are not negligible while coordinated charging barely has any impact on the distribution system at all. The paper concludes that PHEV charging must be coordinated via operators and other multi-agent-systems in order to maintain the integrity of the distribution grid while reducing power loss and voltage drop.

A time coordinated optimal flow model for integrating PHEVs, vehicle-to-grid (V2G), and PHEV storage units and tap changers (OLTCs) in order to minimize power loss and OLTC usage is suggested in Acha et al. [11].

This paper makes two major contributions to the area of modeling PHEV and V2G technology. First, it develops a set of nodal equations that represent PHEVs with V2G technology. These equations take into consideration the effect that PHEVs will have on the net load at any given node. They also split the effect of PHEVs into multiple categories: vehicle-to-grid, grid-to-vehicle, and vehicle-to-road. All three of these effects must be considered anytime that the impact of V2G technology on the grid is considered. Second, the paper establishes a relationship between the impact of V2G technology on the grid and the impact of distributed generation on the grid. In this paper the relationship between these two is seen as one where V2G and distributed generation work in similar manners to limit energy losses.

This paper concludes that V2G will have significant impacts on distribution as it helps reduce energy losses in areas that are further away from the slack bus. An interesting furthering of this study would entail expanding the model to include costs and other energy sources. Another interesting undertaking would be the comparison of V2G technology with distributed generation and distributed storage methodologies. Perhaps models could be developed that model V2G technology and reliability by combining distributed storage and generation models.

An evaluation of the loading of PHEVs on distribution system of Hydro-Quebec is studied in Maitra et al. [12]. The distribution network itself is designed to accommodate cold load pickup during long winter outages. The calculated PHEV load is 2400 kWh per year per vehicle, the same load as a water heater. Based on the number of cars in Quebec, at 25% penetration this would be a 2.4 kWh load, less than 1.3% of Hydro-Quebec's capacity.

The model presented is deterministic and takes into consideration thermal loading, voltage regulation, and transformer loss of life based on a full array of PHEV characteristics (battery type, charger efficiency, battery state of charge, and charging profiles). The deterministic model is run at both a component and system level in order to identify asset sensitivities to new loads.

The model predicts that transformer life will be maintained while service transformers and three-phase primary lines are the most susceptible to issues from the higher loads caused by PHEVs. The model also shows that the key factor in affecting the distribution grid is the charging profile (voltage and power level).

A basic framework for analyzing the impact of PHEVs on local distribution systems is developed in Taylor et al. [13]. In order to get consistent results, the model is applied to multiple utility distribution circuits. The model calculates thermal loading, voltage regulation, transformer loss of life, unbalance, power losses, and harmonic distortion levels for multiple scenarios in both a deterministic and stochastic fashion. Using OpenDSS, this paper concludes that distribution grid issues tend to increase linearly as the penetration of PHEVs increases.

This paper also examines what length of time should be considered when evaluating the impact of PHEVs on the distribution grid. As this paper studies only through 2010, it must be considered that both short and long term analysis must be completed. Short term analysis will allow utilities to prepare for immediate impacts while longer range studies will allow utilities to adjust and accommodate future usage and load.

A methodology of modeling PHEVs using an energy hub technique combined with distributed agents is developed in Galus and Andersson [14], Galus et al. [15] and Galus and Andersson [16]. The basic system presented consists of four parts:

- The energy hub agent represents an area large enough to house multiple PHEVs that are parked.
- PHEVs connected to the energy hub.
- The PHEV manager agent.
- Multiple PHEV agents.

The energy hub agent is responsible for optimally dispatching energy through the minimization of energy costs based on energy inputs and outputs. This is done using techniques such as linear programming. PHEV agents communicate data to the PHEV manager regarding plug capacity, connection time, state of charge, and a personal value that demonstrates an individual PHEVs desire for more energy. The PHEV manager agent is an abstract agent that fulfills the goals of monitoring the PHEVs in the hub, optimally dispatching energy to all PHEVs, and communicating between PHEV agents and the energy hub agent. Interestingly, the formulation in this study also deals with the scenario where PHEV agents report a personal value that is untruthful. The implementation details of these agents can be found, in detail, in the given work.

The model developed here is tested using scenarios of 500, 1000, and 3000 PHEVs. The results demonstrate that the method is useful, works efficiently, and is capable of modeling situations where charging is both proactive and reactive. The model is further developed in Galus et al. [15] and Galus and Andersson [16] where it is integrated with MATSim and used in multiple scenarios for a more complete simulation methodology.

The impact of PHEVs on the distribution grid of multiple cities in Stockholm is studied in Karnama [17]. The cars are modeled as a regular load. The penetration of the PHEVs is varied based upon the population and commercial density of each area and multiple types of both regulated and unregulated charging are modeled. The system is modeled through a combination of PSS/E (Power System Simulation for Engineering) and the Python programming language. PSS/E is used in order to run load flow analysis while Python is used to automate and change the load values for each simulation. This paper also provides a solid methodology for scenario planning with regards to PHEVs. The following steps are proposed:

- Area selection.
- Selection of a day in the year.
- Estimation of number of cars in each area.
- Estimation of penetration growth rate of PHEVs in the area until 2050.
- Estimation of average electricity consumption by a PHEV.
- Selection of a valid charging infrastructure.

Details of these steps can be found in the paper itself. The majority of information used in these steps is either obvious or has been mentioned elsewhere in this paper.

The paper concludes that the residential areas will be problematic with regards to the integration of PHEVs as the concentration of people (and thus PHEVs) is higher in these areas. It is also concluded that regulated charging will allow greater amounts of PHEVs to be integrated with the distribution grid. This study also shows that one area of Stockholm will need further development if greater numbers of PHEVs are to be introduced.

The potential impacts of PHEV integration on electrical grid in California are discussed in Axsen and Kurani [18]. The basis of this study is data collected via an in depth, multi-part, online survey as well as through driving diaries. The survey itself was defined as a priority-evaluator game where all participants were provided with both a PHEV buying guide and a driver's diary before participating. The survey itself asked participants to choose from possible PHEV designs where the cost of the PHEV was based on premium over a conventional vehicle, recharge time, charge depleted (CD) MPG and type, CD range, and charge sustaining (CS) MPG. All of these options could be chosen at different levels depending on price.

The results of this survey covered many areas including recharge access, PHEV design and value, and PHEV energy use scenarios. The paper concludes that the major threat to California utilities is the uncontrolled charging of PHEVs during peak hours while the major benefit to California utilities would be the advent of smart charging in order to take advantage of off-peak periods when charging PHEVs.

The economic viability of PHEVs is presented and studied in Judd and Overbye [19]. This paper first presents the obvious economic benefits of PHEVs: supplementing peak load, supplementing regulation, supplementing reactive power, improving grid security, greenhouse gas reductions, and the higher conversion efficiency of electricity when compared to the internal combustion engine (61% vs. 12.6%). The authors then go on to make the case that PHEVs are beneficial economically through analytical arguments.

The model proposed first suggests a novel method of calculating PHEV penetration levels: U.S. Census data. Based on a July 2006 population of 299.398 million people and peak load of 789,475 MW, a peak load of 2.637 kW per person or 379.24 people per MW is calculated. This is then extended by calculating that there are 2.68 people per house, 141.5 houses per MW of peak load, and 129.05 houses with vehicles per MW of peak load. At 20% PHEV penetration levels that would mean that there should be 25.8 PHEVs per MW of peak load. This method of calculating PHEV penetration levels is then used to study the effect of PHEV penetration at 10%, 15%, 20%, and 25% on multiple test systems where PHEVs are connected to the grid using both 120 and 240 V connections at 15, 20, and 40 A.

The three systems tested are the IEEE 24 bus test system, the IEEE 118 bus test system, and the utility 2574 bus test system. The cost of each model is first calculated using the optimal power flow (OPF) and then the security constrained OPF (SCOPF). These models are then run once more including the PHEVs as generators. In the case of the first two systems, 10% penetration lowers costs roughly 30% and then improvement tapers off leaving system costs at 75–85% of the original SCOPF costs. For the larger system a 10% penetration level lowers costs nearly 80% with 30% penetration improving costs by 150%. This paper, overall, presents a novel method for calculating PHEV penetration levels while also developing a solid argument in support of PHEVs.

The use of photovoltaic (PV) power for the charging of PHEVs is examined in Li et al. [3]. This study considers a PHEV that is a PHEV-40 (capable of driving 40 miles on one electric charge) using a Li-ion battery that is also a SUV as that is the most popular type of car in North America. The most important contribution of this paper is the calculation of the ideal PV panel size in order to charge the PHEV daily. When calculated for those times of year with the most solar radiation the ideal panel size is 20 m^2. When calculated to cover all days of the year, including the worst cases in December, the ideal panel size becomes 78 m^2. The paper concludes that while this is an interesting contribution and the environmental benefits are extremely high, the prohibitive cost of solar panels will most likely stifle this idea.

A real-time model for vehicle-to-grid (V2G) transactions is presented in Venayagamoorthy et al. [20]. A model is built that uses eight three-phase vehicles attached to the distribution grid via step-up transformers. The vehicles are split into two groupings of four where each grouping is considered a Smart Park. These Smart Parks are then connected by a 15 km transmission line. A binary particle swarm optimization (BPSO) algorithm is then implemented in order to develop an optimal charging schedule that maximizes the revenues generated by each vehicle. This model is also extended to test system faults as well as systems containing a larger number of vehicles. All simulations were run using the real-time digital simulator platform (RTDS). The paper concludes that advanced control and coordination methods will be necessary for the charging of PHEVs.

Particle swarm optimization is applied to griddable vehicles in a unit commitment (UC) formulation in Saber and Venayagamoorthy [21]. This study demonstrates a novel formulation of the UC problem with V2G enabled vehicles that is solved using a binary/discrete version of PSO. The formulation is shown to increase grid reliability and reserve while decreasing costs and emissions. The formulation and solution develop a solid bridge between the areas of V2G and UC.

A study of the necessary energy requirements for conversion of U.S. light duty vehicles into PHEVs while also studying the effect this will have on emissions as well as the impact that this change will have on the grid is undertaken in Kintner-Meyer et al. [22]. While this paper draws many conclusions regarding energy requirements and emissions across the 12 NERC regions, they will not be discussed here as they are out of the scope of this paper. Regarding PHEVs' impact on the distribution system, this study suggests that supplying 73% of the energy requirements of the U.S. light duty fleet of vehicles would add an additional load of 910 billion kWh to the electrical grid. This would force the grid to operate at nearly full capacity at all hours of every day. This effectively flattens the current "peak and valley" load that is on the grid and could have a huge impact on reliability while also forcing up wholesale electricity prices (due to demand) and encouraging the development of new generation technologies that are less expensive. This would also most likely mean the eventual use of planned outages in order to perform plant maintenance. Smart charging and V2G technology are suggested as possible solutions to these issues.

A detailed analysis of the economic benefits of PHEVs is examined in Scott et al. [23]. A typical PHEV is assumed to be driven 33 miles per day and is charged using electricity from the grid. Analysis is performed using life cycle cost (LCC) analysis for consumers and electricity cost for utilities. The LCC analysis is performed for Ohio and California where the PHEV is compared to a Honda Civic that gets 35 miles per gallon when gasoline costs both \$3.50 and \$2.50 per gallon. In Ohio the suggested maximum premium that a consumer should pay for a PHEV over a conventional vehicle is \$3000 and \$4600, respectively while the premiums for California are \$2000 and \$3500. Similar analysis is carried out for utilities in both Cincinnati and San Diego and can be found in the paper itself.

While admitting that more economic analysis needs to be done, this paper concludes that there are economic benefits for both consumers and utilities with regards to off-peak charging of PHEVs.

A model integrating wind and PHEVs using the wind deployment system (WinDS) model is developed in Short and Denholm [24]. The PHEVs modeled in this scenario are assumed to be one of two sizes: A PHEV-20 with a 5.9 kWh battery or a PHEV-60 with a 17.7 kWh battery. All PHEVs also have a charging efficiency of 85% and are V2G ready. The majority of charging time per PHEV is assumed to occur in the evening off-peak hours (roughly 60%) with some additional charging occurring between 7 a.m. to 1 p.m. and 6 p.m. to 10 p.m.

The initial study demonstrates that wind installations should increase to roughly 208 GW by 2050. When integrated with a fleet of PHEV-20s the wind installation size increases to 235 GW by 2050 and the PHEV-60 fleet increases the estimated installation of wind power in 2050 to 443 GW. These large improvements occur because the use of PHEVs with V2G technology enables wind energy to compete with common forms of energy, effectively turning wind power into a dispatchable energy source that can compete with the prices of common fossil fuels. This shows the intense benefits that PHEVs combined with V2G technology may be capable of providing.

An intelligent method of scheduling the buying and selling of power via PHEVs with V2G technology is introduced in Huston et al. [25]. This study builds the model around PHEVs parked in a parking garage where the garage holds sets of 50, 500, and 5000 vehicles. Modeling of the PHEVs is done by monitoring multiple aspects of each PHEV. Unlike other studies, this study gives each of these measures and upper and lower bound and then generates the value using uniform random variables. The only variable held constant is the desired state of charge (SOC) of any vehicles' battery upon departure. This value is chosen to be 60%. The other aspects measured (and their bounds) include:

- Battery capacity (10–25 kWh).
- Available capacity (50–100%).
- Arrival time (1^{st} to 23^{rd} hour).
- Departure time (2^{nd} to 24^{th} hour).
- Inverter discharge efficiency (80–95%).
- Battery charge efficiency (80–95%).

A binary particle swarm optimization (BPSO) algorithm is applied to this model in order to develop an optimal power schedule that maximizes the profit for the garage owner. The paper concludes that BPSO is an effective and successful mechanism for determining this schedule.

The effect of multiple PHEV charging scenarios using the National Energy Modeling System (NEMS) [26] is discussed in Li [27]. As the space for this study was limited, the only scenario discussed is that with a penetration level of 110 million PHEVs. The paper concludes that generation expansion will be needed in NERC regions 1, 2, 9, and 10 while different charging strategies affect electrical consumption.

The effects of PHEVs on the Pacific Northwest are examined in Schneider et al. [28] using the SynerGEE Analysis Tool from Advantica's Stoner Software. The major benefit of this study is that the work is done using actual load profile and distribution system feeder data from the Pacific Northwest National Laboratory. The simulation itself is divided into two regions based on feeder attributes and geographic location: The Western Pacific Northwest and the Eastern Pacific Northwest. In each case two different, potential PHEV load profiles are studied. The first profile assumes that PHEVs are charged using 120 V at 15 A using smart charging techniques (the authors note here that when using smart charging, the load profile of the PHEV consumes no more than 1.15 kW which is less than a typical hair dryer). The second profile assumes charging at 240 V and up to 50 A when charging occurs only between the hours of 5 p.m. and 7 p.m. Both profiles are examined using penetration levels of 10%, 25%, 50%, and 100% which translates to 4.3%, 10.8%, 21.6%, and 43.2% of the current light duty vehicle fleet. The authors also make two further assumptions: the average miles driven per day is 33 and all PHEVs are charged at residential receptacles.

This study concludes with nearly identical results for both the western and eastern regions: The 120 V scenario with penetration up to 50% is highly sustainable with the current system while the 240 V scenario without smart charging is never sustainable as it immediately causes faults. While this study suggests that PHEVs using smart charging at a typical 120 V receptacle will be sustainable in the Pacific Northwest, it would be interesting to see the effect that smart charging has on the 240 V scenario.

The effects of PHEV penetration on generation expansion are studied in Yu [29]. This paper uses the NEMS tool and suggests examining four different charging profiles, all at high PHEV penetration levels. These charging profiles include uniform charging, home-based charging, off-peak (9 p.m. to 11 a.m.), and V2G charging. The authors also assume that all PHEV batteries are capable of driving 20 miles and the average consumer drives 33 miles per day. One interesting assumption made is that only 75% of PHEVs can be charged electronically at any given time due to possible infrastructure restrictions (i.e. charging stations not in place, etc.). All simulations are run across the entire United States. The paper concludes that while all charging methodologies produce a need for new sources of power generation while the V2G charging plan causes the smallest capacity expansion and the smallest infrastructure cost.

An extensive report covering the system level impacts of PHEVs on the electrical grid is carried out in Meliopoulos et al. [30]. As this report is extensive and detailed, only the main conclusions that are pertinent to this survey will be reviewed. While the important conclusion in this work is that the main impact of PHEVs on the electrical grid is favorable, some of the other main conclusions are as follows:

- If 10% of the current U.S. vehicle fleet became PHEVs, the electrical load would increase by 31.35 GW.
- Typical household circuit capacity (120 V/20 A) is capable of recharging PHEVs in a sufficient and timely manner.
- Distribution transformers may experience a measurable loss of life (LOL) due to PHEV usage.
- PHEVs have a great potential to save grid operating costs and reduce critical contingencies.
- PHEVs have a significant effect on unenforceable security constrained optimal power flow (SCOPF) contingencies and maximum line over-loads.

The most interesting comment in this report is that though PHEVs may cause transformer LOL, transformer LOL is a problem routinely dealt with by utilities and should not pose a significant threat to the advent of PHEVs as long as the transformers are monitored wisely.

A precise discussion of the effects that PHEVs will have on transformers is developed in Farmer et al. [31]. This study suggests that there may be three main impacts from PHEV integration into the power grid: An increase in transformer temperatures due to increased load, reduced wear-and-tear on the transformer bushings due to flattened load, and increased harmonics due to PHEV power electronics. While the first two impacts may be able to offset each other (reduced wear-and-tear will compensate financially for decreased lifetime due to the increased load) there is concern that power harmonics could have a major impact on transformers. The remainder of the paper develops a mathematical model for examining these impacts and concludes that the impacts will be widely varied in different parts of the power grid.

3. Detailed discussion

3.1. Driving patterns

Driving patterns produce an impact on the distribution grid simply by defining where PHEVs will be when they are charged. A typical daily drive for any person starts at home, goes to work, maybe to lunch, back home, then possibly out for a small trip to the store. This means that at any point during the day a PHEV could possibly be in the garage, in an employer's parking lot, in a restaurant/store parking lot, or on the road. This suggests studying where PHEVs will be when charging and how many of them will be charging at a time.

The truth of the matter is that the final destination of most driving patterns is highly stochastic, but the average mileage driven during any given day has been determined to be roughly 26 miles per day [5]. Thus, the majority of papers calculated the distance consumers drive daily using this statistic. In order to handle the randomness of the locations of the PHEVs, multiple studies simply place the PHEVs randomly across radial distribution networks.

In the future some studies similar to Huston et al. [25] should be undertaken in order to determine where PHEVs will be charged. Surveys must be conducted in order to determine two criteria: where PHEVs will be clustered together (parked) and how high the concentration of PHEVs will be in each cluster. This may have a drastic impact on feeder circuits as additional load may be concentrated in specific areas as cars are parked during the day (a typical peak load time) as well as in the evenings. The economic incentives for businesses to place charging stations in their parking lots should also be examined along with public policy that could encourage such practices. The basis for answering at least part of these questions has been developed in Huston et al. [25], but the study needs to be furthered in order to determine the effects that a parking garage full of PHEVs will have on the distribution system of the electrical grid.

It would also be interesting to conduct studies under purely stochastic models of driving. In other words, instead of using average and expected values for the number of miles driven per day, use stochastic models across multiple simulations in order to get a more realistic picture and analysis of this situation.

3.2. Charging characteristics

Charging characteristics are simply the loading characteristics of PHEVs in different locations. Charging characteristics typically incorporate the type of circuit, the voltage drawn, the load added to the circuit, and the amount of time that charging takes. Multiple papers have defined these characteristics in both similar and slightly differing manners. It will be important to include these characteristics in future studies in order to build accurate models of PHEVs, especially as large manufacturers of vehicles spend much time and money developing batteries and testing procedures (such as in Duvall [32]) that define these charging characteristics. It will also be a requirement that these charging characteristics are continually refined to more accurately reflect real world situations.

A few studies suggest that PHEVs may be connected to the grid at multiple levels as per Table 1 [19,6,5]. The battery is limited to the battery included in the Chevy Volt (detailed in Table 2) in Shao et al. [8]. In [12,13] the charging levels assumed are as detailed in the SAE J1772 specification which is detailed in Table 3. Charging levels of only 120 V/15 A and 240 V/50 A are assumed in Schneider et al. [28].

A single type of vehicle or battery is not assumed by Axsen and Kurani [18]. Instead this study simply gives consumers the option of purchasing a vehicle with a given recharge time of 1, 2, 4, 6, or 8 h.

Table 1
PHEV charging levels.

120 V AC	15 A	1.4 kW load
120 V AC	20 A	2 kW load
240 V AC	30 A	6 kW load

Table 2
Chevy volt battery specifications.

Type	Lithium ion
Energy	16 kWh
Voltage	320–250 V
Charge time	6–6.5 h
Range	40 miles

Table 3
PHEV charging characteristics [33].

Type	Power level
120 VAC	1.2–2 kW
208–240 VAC	2.8–3.8 kW
208–240 VAC	6–15 kW
208–240 VAC	>15–96 kW
600 VDC	>15–240 kW

As demonstrated by the studies shown above, each study has a tendency to define the type of battery or vehicle that is used to simulate impacts on the distribution grid. These assumptions are made in many other papers including but not limited to [34,35] and Kempton and Tomic [36] and Short and Denholm [24]. Axsen and Kurani [18] are alone in attempting to incorporate consumer choice into the process of simulating impacts on the grid based on charge timing and battery choice that affect consumer price. This adds an interesting perspective into modeling the impact of PHEV charging characteristics as it attempts to incorporate economic influences including cost and availability of recharge stations.

Because all batteries are different, because most vehicles will have batteries that have at least slightly different charging profiles, and because it is very unlikely that consumers in any single area will own one, single type of PHEV from a single company, future studies should concern themselves with the distribution of different types of vehicles and batteries in fleets of PHEVs. This will be extremely important as competitors begin to arise and compete with each other over battery life, charging time, and charge duration. The determination of these mixes of vehicles should also be based upon economic data where charging characteristics are determined based on the consumer's willingness to spend more money for a quicker recharging time [18].

Other simulations should also be undertaken to model the effect of aging on the impact of PHEV charging profiles. Perhaps simulating the impact of having mixed fleets of PHEVs where some are brand new, some are a year old, and others are multiple years old could lead to interesting results regarding the impact that this type of fleet diversity will have upon the distribution grid.

3.3. Charge timing

Though the study in Clement et al. [9] concludes that charging level is a better indicator of the impact of PHEVs on the distribution grid, it is also very important to consider precisely when vehicles will be recharged on both the macro- and micro-scale. The macro-scale will include the time and season of the year while the micro-scale will consider daily charging tendencies. It should also be

considered that the base case in all simulation studies should be the case of having no PHEVs in the system [9].

On the macro-scale, the season of the year is important to consider [6–10,37] while some studies go as far as modeling individual days of the year [17]. The typical seasons considered are summer and winter as these are typically peak seasons for both air conditioning and heating, both of which contribute a significant load to the distribution grid. The addition of a PHEV load on top of these two seasonal loads may contribute vastly to the reliability and security of the distribution grid. These loads are considered through the incorporation of low loads (daily load with highest peak plus three random profiles for each season) and high loads (four charging profiles from each season with highest daily average) in Clement et al. [9].

On the micro-scale there are many more options to consider. The simplest charging plan is uncontrolled charging [9,10,12,37] – a charging plan where PHEVs charge any time they are plugged in. This is the base case for all charging scenarios as it is the most likely initial case before market penetration of smart technologies and the advanced metering infrastructure (AMI). This methodology is also called uniform charging [29]. The next simplest of these is the early evening vs. night charging [6]. A variation of this is found in New York ISO [5] where night and evening charging are both considered using multiple loads: 1.4, 2, and 6 kW. A further variation of this may be found in Shao et al. [8] as quick charging is added into the mix of both evening (after 6 p.m.) and off-peak charging. Quick charging is simply a method of charging that allows a vehicle to draw a higher load in order to charge much faster, usually around 240 V on a 30 A circuit [8]. Still another variation is found in Yu [29] where home-based and off-peak (9 p.m. to 11 a.m.) are considered.

A slightly different definition of both regulated and unregulated charging plans is suggested in Karnama [17]. Here unregulated charging is defined as charging when little or no information is available about the price of electricity. Regulated charging is defined as charging based on incentives or information that would coerce people into charging their PHEVs at specific times of the day.

Another method of defining charge timing is found in Schneider et al. [28]. Here, the authors assume that PHEVs are charged at either 120 V using smart charging or at 240 V between the hours of 5 and 7 p.m.

The most advanced of charging profiles are those that incorporate smart technology into the charging system and distribution grid. These possibilities are considered through the addition of stagger charging and household load control [8,37]. Stagger charging is typical smart charging where a PHEV throttles its charging based upon predefined power levels communicated through the electrical grid. Household load control is a novel idea that would allow homes to shed non-essential loads in order to charge PHEVs either fully or more quickly. Smart charging techniques using embedded smart technology are examined in Acha et al. [11] while Yu [29] considers smart charging via V2G technology.

The use of binary particle swarm optimization (BPSO) is considered in Huston et al. [25], Venayagamoorthy et al. [20]. In both cases the BPSO is used to formulate a global schedule of the buying and selling of power in order to maximize revenues for all vehicles.

A very interesting set of charging scenarios is considered in [11], mainly because the model incorporates combined heat and power units. The scenarios considered can be seen in Table 4. Another interesting facet of this study is that it incorporates vehicle-to-grid technology [35]. This adds a new dimension to charging scenarios as the PHEV may contribute electricity back to the grid (vehicle-to-grid or V2G) instead of drawing electricity from the grid (grid-to-vehicle or G2V).

Table 4
PHEV charging scenarios.

PHEV/CHP penetration	Grid-to-vehicle	Vehicle-to-grid
10	10 p.m. to 6 a.m.	6 a.m. to 10 p.m.
10	9 p.m. to 9 a.m.	9 a.m. to 9 p.m.
10	Continuous	Continuous
30	10 p.m. to 6 a.m.	6 a.m. to 10 p.m.
30	9 p.m. to 9 a.m.	9 a.m. to 9 p.m.
30	Continuous	Continuous

Charge timing scenarios similar to those above with the addition of enhanced workplace access is proposed in Axsen and Kurani [18]. This is simply a methodology where consumers are able to recharge their vehicle at work. In other words, it is uncontrolled charging assuming that there are charging stations at the workplace.

Another interesting method of charge timing is found in [14–16]. In these papers charging typically occurs where there are large concentrations of PHEVs such as parking garages. In these cases the charge timing is based upon driving habits and is further controlled by centralized agents that optimize and schedule charge timing within these entities.

Overall, multiple charging plans must be considered not only in order to build thorough studies, but also because consumers will tend to behave randomly when it comes to charging PHEVs. Until smart technologies are in place that can throttle and regulate the load contributed to the grid through charging of PHEVs, it must be considered that consumers will continue to charge their vehicles rationally, irrationally, and randomly.

Future studies should continue to examine the charging scenarios detailed in this section while also incorporating new charging scenarios that are based on more, newer stochastic models while also considering further implications of smart charging and what impact it will have on the distribution grid. An interesting study could be undertaken by combining multiple charging scenarios in a single simulation. This will lead to much more realistic and applicable results, especially as an aging fleet of PHEVs stays on the road. Perhaps the oldest PHEVs on the road could charge randomly, slightly newer vehicles will be able to start and stop charging but will always charge at a steady power draw, and the newest vehicles will function under the influence of smart charging where both charge timing and power draw can be throttled and even, in the case of V2G, reversed.

Another interesting problem is presented in Huston et al. [25] and Venayagamoorthy et al. [20]. The development of charge scheduling inside fixed groupings of PHEVs (parking lots, parking garages, etc.) provides an area ripe for the development and application of new scheduling algorithms and computational methods.

3.4. Number of vehicles and penetration

The penetration level of PHEVs will certainly have a drastic impact on the distribution grid. Multiple studies use very similar and realistic statistics to determine the market share and penetration of PHEVs while other studies build up models simply for analysis. The studies considered in this paper consider PHEV market penetration as follows:

- Market share is expected to be 25% by 2018 for PHEV-20 vehicles [6].
- 9% penetration giving roughly 1 PHEV per five houses [8].
- 25% of fleet is PHEVs by 2030 [5].
- 30% in Belgium by 2030 [10].

Table 5
Penetration of PHEV per customer.

Market penetration	PHEVs per customer		
	0	1	2
2%	96.9	3.1	0.0
4%	93.8	6.1	0.1
8%	87.8	11.6	0.5

- 25% at 2.4 kWh per year. 50% by 2030 [12].
- 2%, 4%, and 8% for component based analysis and 0–20% for system based analysis [13].
- Levels are based on data from the U.S. Census Bureau [19].

An interesting consideration of market penetration of PHEVs can be found in Table 5 [13]. This analysis of PHEV penetration calculates the probability that a given customer will have 1, 2, or 3 PHEVs in their home. This is a wise consideration as most homes, especially in the U.S., have multiple vehicles.

The use of surveys and driving diaries determines market share in Axsen and Kurani [18]. This is the most realistic estimate of PHEV penetration given as it is based on actual consumer response instead of statistical projection.

It is our thought that the above penetration scenarios are sufficient for all studies and are based on solid data. Though, in the future it will be necessary to adjust all of these models based upon the reality of PHEV sales and usage. The most novel and appropriate model of PHEV penetration is found in Taylor et al. [13] where a typical home in the U.S. has multiple vehicles. Another novel approach is found in Axsen and Kurani [18] as the assumptions are based on consumer surveys. This type of data should definitely be collected and used as a guide for future studies.

In the future it will be certain that penetration studies should also take into consideration both location (rural, urban, and suburban) as well as income and education levels in order to simulate how many PHEVs a given household or area may contain.

3.5. Metrics used

An important aspect of analysis regarding the impact of PHEVs on the distribution is the metrics used to gauge their impact on the power system. A solid foundation for this is set in Taylor et al. [13] by measuring thermal loading, voltage regulation, transformer loss of life, unbalance, losses, and harmonic distortion levels. These are typical metrics for both systemic and component based analysis, though they are lacking in some regards. It should be noted that it will be very important to continue the modeling of system level components when dealing with PHEVs. This is because the added loading and discharging of PHEVs and V2G technology will have a large impact on individual components, not only the system as a whole.

Cost is also an important measurement of any model as the true force driving change and technology alike is economic viability. This is shown in Judd and Overbye [19] where the focus is on reducing costs related to power flow through the use of PHEVs.

A further measurement that should be obtained is the reliability of the distribution grid under the added load of PHEVs and V2G. This would require building models that would calculate the typical reliability measure for the distribution grid: System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Customer Average Interruption Frequency Index (CAIFI). This is very important as utilities use these measures in the planning and analysis of their own distribution grids. Future studies should certainly include these measures and should build new models that aid in the calculation of these measures.

3.6. Tools used

The modeling required to integrate PHEVs with the distribution grid is of great importance as the results achieved are only as valid as the models that are used. The studies reviewed in this paper use many different models, tools, and techniques in order to produce results from their simulations and studies.

As with any developing area of research, many models must be developed and pursued in order to gain insights into building a realistic and reliable model. In many cases this is done through the modeling of a region or section of the actual distribution grid. This can be seen in Maitra et al. [12] where two actual feeder circuits are used in order to plan for live systems. In other cases scaled down versions and test systems may be used. An IEEE 24 node test feeder scaled from 24.9 kV to 230 V is used in Clement et al. [9]. The study also randomly chooses loading scenarios with different PHEV penetrations and PHEV placements. Other studies, such as Taylor et al. [13], simulate loads at random PHEV penetration levels. While these models may not be entirely realistic, they provide a good idea of what impacts PHEVs will have in a basic feeder circuit. In the future, more realistic models should be built based upon different countries and their regions. While small models are always of benefit as a starting point for analysis, only large and realistic models can and will be truly useful for planning and development in the future.

Once a model is developed and planned out it becomes necessary to determine what tools will be used to complete the simulation and gather results. Studies such as Shao et al. [8] and Taylor et al. [13] use Matlab/SimuLink for battery modeling and OpenDSS for load modeling respectively. WinDS is used in Short and Denholm [24].

A method of analysis using both Quadratic and Dynamic programming is developed in Clement et al. [10]. Each of these methods is further broken down into stochastic and deterministic models. The input to all models is the hourly load. In the case of the stochastic models, the hourly load is transformed into a probability density function where the standard deviation for 99.7% of cases the value of the sample is within a band of 5% or 25% of the actual value for each time step [10]. The deterministic model simply generates 2000 stochastic load profiles and calculates the results for each. The stochastic method takes 2000 independent samples, calculates the stochastic optimum, and then calculates the power loss. In the end the quadratic programming method is declared the better method as it produces slightly better results and takes less time to run.

Linear programming models that include the classical techniques of optimal power flow and security constrained optimal power flow are presented and used well in Judd and Overbye [19] in order to estimate cost reductions via the penetration of PHEVs.

A real-time digital simulation (RTDS) platform is used in Venayagamoorthy et al. [20] in order to model multiple sets of Smart Parks where each park contains multiple vehicles.

A deterministic model that analyzes the given system on both the component and system level is built in Maitra et al. [12]. At the component level thermal capacities and transformer loss of life are calculated. At the system level loading and voltage response are measured.

Models for electrical storage that incorporate V2G in the model are developed in Acha et al. [11]. The final model is a time coordinated optimal power flow model that employs a multi-objective formulation which minimizes energy losses while employing PHEV storage units and tap changer devices as infrequently as possible while also assuring that all operational

boundaries are met. The model is highly non-linear and works well.

The use of PSS/E and the Python programming language is suggested in Karnama [17] in order to build automated load flow models of specific systems that integrate PHEVs. This modeling technique seems to work well as multiple simulations can easily be run. The data is also exported to comma separated value (CSV) format in order for analysis in Matlab.

What is, perhaps, the most promising of all models concerning PHEVs is developed in Galus and Andersson [14], Galus et al. [15] and Galus and Andersson [16]. The integration of MATSim and the energy hub method seems to present an ideal opportunity to combine the stochastic habits of drivers with detailed analysis. It is also a novel idea that the simulation be separated into two distinct parts: the travel simulation (MATSim) and the power system simulation using the energy hub method. This allows a great amount of freedom in modeling and analysis. One step that should be taken is the refactoring of MATSim to allow multiple driving patterns to co-exist. As it currently stands, MATSim eliminates poor driving patterns through evolutionary algorithms that slowly redefine each agent's driving habits. While this methodology works well for optimization, it is not an accurate demonstration of everyday life as not all drivers follow optimal driving habits. This model could also be extended to incorporate vehicle-to-grid technologies while also incorporating other economic factors and optimal bidding and energy scheduling policies.

Surveys and driving diaries are used to collect consumer information regarding consumers' willingness to buy PHEVs as well as what types of PHEVs they will buy in Axsen and Kurani [18]. This is very important as it is an attempt to model actual consumer behavior instead of just using projections. Surveys of consumer opinion should be a very important tool as models for PHEVs are continually refined in order to provide better results.

As models continue to be developed and expanded to quantify the impact of PHEVs on the distribution grid, it will be necessary to combine many of the techniques and models listed above. It will also be necessary to increase the level of stochasticity in the models in order to account for consumer behavior. We believe that future models should consider PHEVs, V2G technology, smart charging, and random consumer behavior while becoming more and more realistic, perhaps by using consumer surveys and methodologies similar to those in Axsen and Kurani [18].

3.7. V2G

One interesting aspect of PHEVs is the possibility of V2G integration. Kempton and Tomic [35] define V2G enabled PHEV as a PHEV that has three characteristics: A connection to the grid for electrical energy flow, control or logical connection necessary for communication with the grid operator, and controls and metering on-board the vehicle. V2G enabled vehicles transfer electricity both to and from the power grid as necessary. This intelligent and bidirectional flow is at the core of V2G technology. Kempton and Tomic [35] also describes the fundamental calculations for costs and power that are associated with V2G technology and the potential markets in which they can and should be used. These cost models and suggestions for the market usage of V2G technologies along with those found in Kempton and Tomic [38,36] should be used as a basis for all modeling of V2G technology and its impact on the distribution grid. These papers are especially important as they define the limiting factors of use and electricity transmission for V2G technology. Further discussion of V2G, its characteristics, benefits, flaws, economics, and technical specifications can be found in Clement et al. [33], Sutanto [39], Brooks [40] and Srivastava et al. [41].

It is noted that the wind profile in New York matches PHEV charging needs very well in New York ISO [5]. This would allow two important things: PHEVs could be charged at times when power supplied by wind power is the greatest and V2G technology could be used to store the energy produced by wind turbines. This would obviously impact the distribution grid as V2G enabled PHEVs could actually act as distributed generators in order to stabilize the grid which would lower energy costs and energy losses [11]. This will also affect the distribution grid as there will be an extra load added by the PHEVs.

The most interesting conclusion in any of the papers reviewed here is found in Acha et al. [11] where it is concluded that V2G technology perform in a manner that is strikingly similar to distributed generation as it supplies power when power is needed and consumes and stores power when there is an excess. Because of this, it will be very interesting to see what the advent of new models that treat V2G as distributed generators will bring forth.

4. Conclusions

This paper has presented an overview of the state of the art in measuring and modeling the impact that PHEVs will have on the distribution grid. These impacts are built through a combination of driving patterns, charging characteristics, charge timing, and vehicle penetration.

At this time, while progress has been made, there is much more left to accomplish. We believe that a very hopeful option for furthering the analysis of these areas will be the combination of MATSim and power simulation systems [14–16].

While all of these areas will continue to add valuable information and study to this field, one important step that must be made is the modeling and calculation of reliability indices with PHEVs in place. This means that future studies must begin calculating SAIDI, SAIFI, CAIDI, and CAIFI in order to give an accurate measure of what impact PHEVs will truly have on the distribution grid as reliability is one of the most important aspects of the electrical grid.

References

[1] IEEE USA. Plug-in electric hybrid vehicles. Position statement adopted by IEEE-USA board of directors; 2007.
[2] Duvall M. Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles. Technical Report of EPRI 2002.
[3] Li X, Lopes LAC, Williamson SS. On the suitability of plug-in hybrid electric vehicle (phev) charging infrastructures based on wind and solar energy. IEEE Power & Energy Society General Meeting 2009;1–8.
[4] Dickerman L, Harrison J. A new car, a new grid. IEEE Power and Energy Magazine 2010;8(2):55–61.
[5] New York ISO. Alternate route: electrifying the transportation sector. Technical report. NY: New York ISO; 2009.
[6] Hadley SW. Impact of plug-in hybrid vehicles on the electric grid. Technical report ORNL/TM-2006/554. TN: Oak Ridge National Laboratory; 2006.
[7] Denholm P, Short W. An evaluation of utility system impacts and benefits of optimally dispatched plug-in hybrid electric vehicles. Technical report. National Renewable Energy Laboratory; 2006.
[8] Shao S, Pipattanasomporn M, Rahman S. Challenges of PHEV penetration to the residential distribution network. 2009 IEEE PES General Meeting 2009; 1–8.
[9] Clement K, Haesen E, Driesen J. The impact of charging plug-in hybrid electric vehicles on the distribution grid. In: Proceedings 2008-4th IEEE BeNeLux young researchers symposium in electrical power engineering; 2008. p. 1–6.
[10] Clement K, Haesen E, Driesen J. Stochastic analysis of the impact of plug-in hybrid electric vehicles on the distribution grid. In: Electricity distribution, 2009. CIRED 2009. 20th International conference on electricity distribution; 2009.p. 1–4.
[11] Acha S, Green T, Shah N. Effects of optimised plug-in hybrid vehicle charging strategies on electric distribution network losses. In: PES, editor. Conference and exposition on transmission and distribution. Prague: IEEE; 2010. p. 1–6.
[12] Maitra A, Kook KS, Giumento A, Taylor J, Brooks D, Alexander M, et al. Evaluation of PEV loading characteristics on Hydro-Quebecs distribution system operations. In: Electric vehicle symposium 24; 2009.p. 1–11.

[13] Taylor J, Maitra A, Alexander M, Brooks D, Duvall M. Evaluation of the impact of plug-in electric vehicle loading on distribution system operations. In: Power & Energy Society General Meeting 2009; 2009.p. 1–6.
[14] Galus M, Andersson G. Demand management of grid connected plug-in hybrid electric vehicles (PHEV). In: IEEE energy 2030 conference; 2008.p. 1–8.
[15] Galus M, Waraich R, Balmer M, Andersson G, Axhausen KWB. A framework for investigating the impact of PHEVS. In: Proceedings of international advanced mobility forum (IAMF). Geneva, Switzerland: ZurichETH, Swiss Federal Institute of Technology, IVT Institute for Transport Planning and Systems; 2009.
[16] Galus MD, Andersson G. Integration of plug-in hybrid electric vehicles into energy networks. In: 2009 IEEE Bucharest power tech conference. 2009. p. 1–8.
[17] Karnama A. Analysis of integration of plug-in hybrid electric vehicles in the distribution grid. Master's thesis. Stockholm, Sweden: Royal Institute of Technology; 2009.
[18] Axsen J, Kurani KS. Anticipating plug-in hybrid vehicle energy impacts in California: constructing consumer-informed recharge profiles. Transportation Research Part D Transport and Environment 2010;15(4):212–9.
[19] Judd S, Overbye T. An evaluation of PHEV contributions to power system disturbances and economics. In: 40th North American power symposium. 2008. p. 1–8.
[20] Venayagamoorthy GK, Mitra P, Corzine K, Huston C. Real-time modeling of distributed plug-in vehicles for V2G transactions. Energy Conversion Congress and Expo ECCE 2009.
[21] Saber AY, Venayagamoorthy GK. Intelligent unit commitment with vehicle-to-grid—a cost-emission optimization. Journal of Power Sources 2010;195(3):898–911.
[22] Kintner-Meyer M, Schneider K, Pratt R. Impacts assessment of plug-in hybrid electric vehicles on electric utilities and regional U.S. power grids: part 1: technical assessment. In: 2007 electric utilities environmental conference; 2007.
[23] Scott MJ, Kintner-Meyer M, Elliot DB, Warwick WM. Impacts assessment of plug-in hybrid electric vehicles on electric utilities and regional U.S. power grids: part 2: economic assessment. In: 10th annual EUEC conference; 2007.p. 1–19.
[24] Short W, Denholm P. A preliminary assessment of plug-in hybrid electric vehicles on wind energy markets. Technical report. National Renewable Energy Laboratory; 2006.
[25] Huston C, Venayagamoorthy GK, Corzine KA. Intelligent scheduling of hybrid and electric vehicle storage capacity in a parking lot for profit maximization in grid power transactions. IEEE Energy 2030 2008.
[26] Gabriel SA, Kydes AS, Whitman P. The national energy modeling system: a large-scale energy-economic equilibrium model. Operation Research 2001;49(1):14–25.
[27] Li Y. Scenario-based analysis on the impacts of plug-in hybrid electric vehicles' (PHEV) penetration into the transportation sector. In: IEEE international symposium on technology and society; 2007.
[28] Schneider K, Gerkensmeyer C, Kintner-Meyer M, Fletcher R. Impact assessment of plug-in hybrid vehicles on Pacific Northwest distribution systems. In: 2008 IEEE power and energy society general meeting – conversion and delivery of electrical energy in the 21st century; 2008.p. 1–6.
[29] Yu X. Impacts assessment of PHEV charge profiles on generation expansion using national energy modeling system. In: 2008 IEEE power and energy society general meeting – conversion and delivery of electrical energy in the 21st century; 2008.p. 1–5.
[30] Meliopoulos S, Meisel J, Cokkinides G, Overbye T. Power system level impacts of plug-in hybrid vehicles. Technical report. Power Systems Engineering Research Center (PSERC); 2009.
[31] Farmer C, Hines P, Dowds J, Blumsack S. Modeling the impact of increasing PHEV loads on the distribution infrastructure. In: 43rd Hawaii international conference on system sciences. 2010. p. 1–10.
[32] Duvall M. Battery evaluation for plug-in hybrid electric vehicles. In: IEEE vehicle power and propulsion conference; 2005.
[33] Clement K, Haesen E, Driesen J. Electric vehicle conductive charge coupler. In: Electric vehicle conductive charge coupler. 2009. p. 1–32 [SAE J1772, recommended practice, draft document in progress 2009].
[34] Kempton W, Kubo T. Electric-drive vehicles for peak power in Japan. Energy Policy 2000;28(1):9–18.
[35] Kempton W, Tomic J. Vehicle-to-grid power fundamentals: calculating capacity and net revenue. Journal of Power Sources 2005;144(1):268–79.
[36] Kempton W, Tomic J. Using fleets of electric-drive vehicles for grid support. Journal of Power Sources 2007;168(2):459–69.
[37] Putrus G, Suwanapingkarl P, Johnston D, Bentley E, Narayana M. Impact of electric vehicles on power distribution networks. In: IEEE vehicle power and propulsion conference. 2009. p. 827–31.
[38] Kempton W, Tomic J. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. Journal of Power Sources 2005;144(1):280–94.
[39] Sutanto D. Alternative energy resource from electric transportation. In: First international conference on power electronics systems and applications proceedings. 2004. p. 149–54.
[40] Brooks A. Integration of electric drive vehicles with the power grid – a new application for vehicle batteries. In: The seventeenth annual battery conference on applications and advances. 2002. p. 239–54.
[41] Srivastava AK, Annabathina B, Kamalasadan S. The challenges and policy options for integrating plug-in hybrid electric vehicle into the electric grid. The Electricity Journal 2010;23(3):83–91.